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Low-Cost Space-Based Geoengineering: An Assessment Based on Self-Replicating Manufacturing of in-Situ Resources on the Moon

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***Abstract*—**Geoengineering approaches to climate change mitigation are unpopular and regarded with suspicion. Of these, space-based approaches are regarded as unworkable and enormously costly. Here, a space-based approach is presented that is modest in cost, fully controllable and reversible, and acts as a natural spur to the development of solar power satellites over the longer term as a clean source of energy. The low-cost approach exploits self-replication technology which it is proposed may be enabled by 3D printing technology. Self-replication of 3D printing platforms will enable mass production of simple spacecraft units. Key elements being developed are 3D-printable electric motors and 3D-printable vacuum tube-based electronics. The power of such technologies will open up enormous possibilities at low cost including space-based geoengineering.

***Keywords*—**3D printing, in-situ resource utilization, self-replication technology, space-based geoengineering.

I. Introduction

LITTLE of effect has been achieved in reducing the rate of global greenhouse gas emissions, let alone its accumulation. Human activities are reaching the limits of Earth's capacity to a self-regulating system to return to its natural state [1]. Geoengineering has been proposed as a necessary emergency stop-gap to stop global warming from spiraling out of control [2]. There is two main approaches to geoengineering to alter the Earth's thermal balance: (i) removal of CO_2 from the atmosphere to be sequestered safely; (ii) reduce solar radiation to Earth by reducing solar flux to Earth or by increasing Earth's albedo. An excellent technical review of the various geoengineering proposals has been outlined in Lenton & Vaughan (2009) [3]. They suggest that of all the various schemes proposed, only space-based geoengineering and stratospheric aerosols are capable of providing sufficient uniformity of greenhouse warming mitigation with scalability to the global application. These other geoengineering approaches require deployment in combination to gain global scale effects. Many require a significant investment of energy and materials (which themselves require energy to produce). Only space-based approaches in conjunction with the use of space resources offer the prospect of minimizing the use of Earth resources and its detrimental side effects. Space-based geoengineering using solar shields (sunshades) accomplishes the same thing as sulfate particles injected into the troposphere by reducing the solar constant but without polluting the atmosphere and potentially endangering the Earth's biosphere. Space-based geoengineering may not be subject to most geoengineering bans as it is applied off Earth and does not involve direct interaction with the Earth's biosphere. They are therefore subject to fewer side effects and so more potentially predictable. Solar shields involve the manipulation of only a single parameter – incident solar flux to Earth – and do not involve any chemical intervention with the Earth's environment. A combined strategy of geoengineering with fossil fuel curtailment would entail geoengineering providing sufficient time to effect reductions in greenhouse gas emissions [4].

The Early approach to space-based geoengineering involved the construction of a large Fresnel lens of glass to be delivered to the Lagrangian point at L1 between the Earth and the Sun [5]. At L1, reduction of solar radiation to the Earth by 2% requires a shield of 2000 km diameter and 10 μm thick massing 100 Mtonnes -this represents a minimum mass for a solar shield [6]. The shield refracts light rather than reflecting it to minimize solar photon perturbations. Given that global warming is increasing over time, it may be necessary to increase the size of the solar shield accordingly incrementally. A more recent suggestion involves launching from Earth 16 x 10^{12} small glass disks of 60 cm diameter to near L1 (nominally at 185 Mkm from Earth) forming an elongated cloud with an elliptical diameter of 6200 x 7200 km and thickness of 100,000 km [7] (Fig. 1).

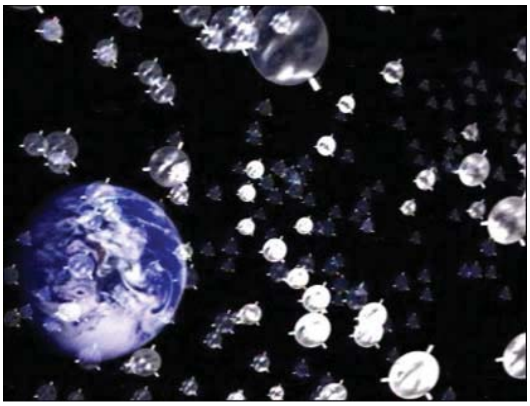

Fig. 1 Swarms of optical disks forming a cloud near Sun-Earth L1

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This distributed approach eliminates the problem of the on-orbit assembly of a large shield but introduces the problem of relative coordination of the constellation. The use of active spacecraft rather than passive dust particles ensures that the constellation can be maintained in a stable configuration for as long as desired. Each optically transparent disk of silicon nitride would be 5 μm thick with half its area devoted to precision-manufactured stepped optical profile holes forming a refractive screen with reflection coatings. To maintain relative position, each disk requires a radio receiver similar to GPS to measure relative position and speed. Each disk would be embedded into a larger reflecting solar sail that can be maneuvered to maintain their position and attitude by modulating radiation pressure through tilting. An appropriate sail design would be the helio-gyro in which a small number of outer tilted vanes mounted about the central disk hub provide rotation. Each disk has a very low areal density of 4.2 g/m^2, low reflectivity of 4.5% and a mass of 1.2 g totaling 20 M tons. The disks would be launched up high altitude mountains on Earth by 20 x 2 km long electromagnetic railguns firing a 1-tonne stick of 800,000 disks every 5 minutes for 10 years. Each stick would be encased in ablative heat shielding with a minimized drag configuration for firing through the Earth's atmosphere. Each disk refracts sunlight a few degrees away from the Earth to reduce solar flux to Earth by 1.8%. This would effectively counteract most of the 2% greenhouse warming predicted by CO_2 doubling for 2050. Refraction through the optical disk minimizes the photon pressure compared with reflection. The glass would be required to maintain its optical qualities against solar darkening for around a 50-year projected lifetime. Each stack would deploy to L1 using solar-powered ion propulsion using 150 kg of Ar fuel. The ion propulsion system is required to deliver a delta-v of 1 km/s at low thrust from GTO around Earth to L1. Similar orbital maneuvers would be required from low lunar orbit. Ar propellant is course is available in low quantities from lunar volatiles. There are further variants on the solar shield. A Near-Earth asteroid may be towed to gravitationally anchor a cloud of dust near L1 [8], [9]. Another is to generate a ring of particles or small spacecraft around the Earth in the range 1.2-1.8 R_E to shade the tropics alone and moderate the climate [10]. Similarities in the fundamental technologies of the solar shield and a solar power satellite, particularly the trend toward distributed formations of simpler units over complex, monolithic spacecraft offering advantages of greater availability [11]. To combine geoengineering with space-based power generation, a 700,000 km^2 parasol may be overlain with 500,000 km^2 of photovoltaic cells at L1, but this would require higher frequency millimeter waves to reduce diffraction spreading over longer distances at the cost of greater atmospheric absorption [12].

II. Summary of Approach

These proposed approaches to space-based geoengineering are infeasible requiring the launch of an enormous mass of material into the L1 point. They are however worthy of further consideration as space-based geoengineering is the only approach that is implementable in structured phases, fully controllable and fully reversible once implemented. Our approach is to eliminate the launch problem entirely by exploring the possibility of utilizing extraterrestrial material for robotic construction. This is in-situ resource utilization (ISRU) for which the forthcoming Resource Prospector Mission (2018) to the Moon will be a technological demonstrator. In this paper, the processing of lunar in-situ resources is explored as a technological lever to enable low-cost approaches to space-based geoengineering in the construction of a solar shield. Specifically, this lunar mission will demonstrate the extraction of lunar oxygen, impregnated volatiles and iron from the common lunar mineral ilmenite. Supplemented with Ni-Fe asteroid material at a number of lunar locations similar to the Sudbury Astrobleme, this provides the basic raw materials (a range of iron alloys, silicone plastics, glasses, cement, and ceramics) to achieve a significant infrastructure. As part of this infrastructure, we envisage constructing a 3D printer based mechanism using these materials. It is postulated that the 3D printer mechanism effectively constitutes a universal constructor -a theoretical concept that is capable of constructing any machine given the appropriate program, energy and raw materials. If so, a corollary of this is that the 3D printer can self-replicate copies of itself. This can be exploited through the implementation of a self-replicating machine deployed onto the Moon to manufacture [13], using local lunar resources, the manufacturing capacity to build a solar shield system and a solar power satellite system. One of the most important considerations for a self-replicator is material and component closure [14] - simplicity is the key. In particular, we have concentrated on the development of 3D printable mechatronic components, i.e., electric actuators, electronics, and sensors. These are the key components in any type of robot mechanism, be it a 3D printer, robotic manipulator, rover vehicles, further manufacturing machines, etc. We present our efforts and results in demonstrating 3D printing of electric motors and vacuum tube based electronics. Although still ongoing, our work suggests that there are no major technological hurdles to 3D printing electric motors and vacuum tube electronics. These components also provide the mechanisms for energy generation on the lunar surface. This effectively demonstrates the core feasibility of self-replication of productive capacity on the Moon. This offers the prospect of exponential growth in productive capacity from lunar resources; this is the key to extremely low-cost implementation of a distributed solar shield. Given that the same technology can be used to manufacture constellations of solar power satellites, this refutes the notion that geoengineering will distract effort from causative solutions based on clean energy.

III. Self-Replicating 3D Printers

A universal constructor is a machine that can manufacture any machine (a construction version of a Turing machine). This includes a copy of itself, i.e., a universal constructor is also a self-replicating machine. Such a machine can construct any number of copies of itself extremely rapidly – its population grows as ~$(x+1)^n$ where x=number of offspring per generation and n=generation number. Self-replication acts as an economic exponentiator. If a 1-tonne seed factory were launched to at the cost of $2B, the specific cost for 1 million copies in under 13 generations would have dropped from $2M/kg to only $2/kg. Once replicated, the machines may be re-programmed to manufacture the desired spacecraft units – in this case, the modules of a solar shield. Each of the 1M units of the self-replicating population would have to manufacture 1M shield units to obtain the 10^{12} or so modules required. Alternatively, larger 1 kg units of 15 m^2 would reduce the number of solar shield units to 10 B units, i.e., 10,000 shield units each.

The Chirikjian-Sukathorn lunar seed factory was estimated to be 5 tons in mass comprising two robots with a payload (of two manipulators, a bulldozer shovel, and material grinder/separator) of combined mass of 1500 kg plus a 1000 kg furnace and 2,500 kg of the solar array to cover 100 m^2 area [15]. The Chirikjian-Suthakorn demonstration was based on Lego Mindstorms kits comprising a system of robots capable of assembling component modules into replicated robots. Though simple in scope, this was a significant practical demonstration. It did not, however, address the material or component closure problem.

One of the most versatile manufacturing techniques is additive/layered manufacturing (colloquially, 3D printing) of which several techniques are relevant here. Indeed, 3D printers can construct physical configurations that are unachievable by other means of manufacturing. All 3D printers are effectively Cartesian robots constituting a workpiece platform and a printing head that move in 3D relative to each other driven by motors. Selective laser sintering (SLS) is versatile in that it can print many different materials including metals, plastics, and ceramics, but SLS machines are complex in construction and often yield inferior performance to other methods. Fused deposition modeling (FDM) can print a variety of plastics including silicone plastics. Experiments have been conducted to demonstrate the viability to using lunar regolith with a binding fluid to 3D print buildings in almost any shape [16]. The RepRap 3D printer is an example of FDM 3D printing that can print its own plastic parts [17] (Fig. 2).

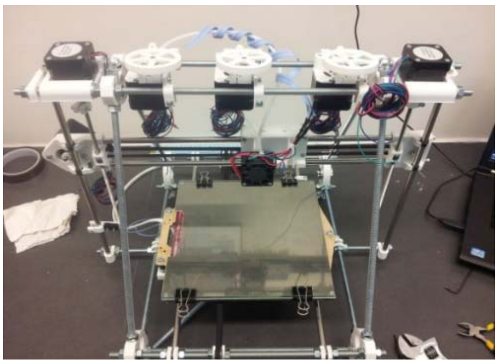


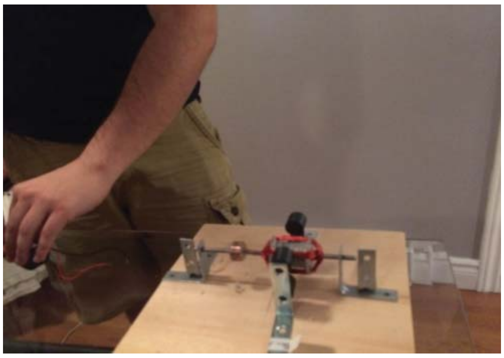
Fig. 2 Replicating Rapid Prototyper (RepRap) 3D printer

The chief limitation in 3D printing, unfortunately, is that they can only manufacture structures, albeit highly complex structures. If RepRap were to print its metal bars, joiners, motors, electronics and be able to self-assemble, it would effectively constitute a self-replicating machine. Joinery may be implemented with cement/adhesives rather than threaded nuts and bolts (indeed, 3D printing significantly reduces joinery by manufacturing monolithic structures). There are sufficient raw materials on the Moon to form cement, especially from anorthosite which comprises 19% lime (CaO) [18]. Metals products have traditionally been prepared by powder metallurgy or casting. However, electron beam freeform fabrication (EBF3) may be used to print metal [19] - it is based on the electron gun, a variation on the vacuum tube. The electron beam is generated by an electron gun, and a series of magnetic lenses form an electron probe at the work surface. A similar technology - electric discharge machining (EDM) - adopts a pulse voltage discharge between the electrode tool and the workpiece to remove some material - in a way, it is the inverse of EBF3. EDM is a versatile method of manufacturing complex 3D microstructures with cavities and contours such as tooling and involute gear teeth [20]. Assembly may be performed by robotic manipulators or wrists that are constructed from motors configured serially rather than in the Cartesian configuration of the 3D printer. This is reconfigurability where robotic modules can be assembled into different configurations for different tasks [21]. The application of such reconfigurability has considerable implications for rapid response manufacturing [22]. The chief challenge then is to be able to 3D print, either directly or indirectly, motors and electronics. This is the central thrust of this work -an electric motor system is an integrated unit comprising an actuator, control electronics, and sensors, and the corollary presented is that if an electric motor *system* can be 3D-printed, the 3D-printer constitutes a universal constructor capable of self-replication. It can construct other motorized tools that constitute a typical fabrication laboratory -lathes, milling machines, drill presses, bending presses, compression presses, extruders, centrifugal ball mills, etc. With 3D-printed electric motor systems, 3D-printed robotic manipulators and vehicles such as JCBs, haulers, mining cutters, drills, etc. can be constructed.

IV. Mechatronic Components in Robots

A simple electromagnet/solenoid with switches was proposed as a standard self-replicating unit to assemble multiple such units within a sea of units [23]. A similar set of electromagnetic units to be self-assembled was outlined [24]. Assembly of components and parts into subsystems and systems is an essential part of self-replication. In both cases, assembly was controlled by electromagnetic attraction/ repulsion. This indicates the central role of actuation mechanisms in self-assembly. A 3D-printed electric motor would enable assembly tasks to be conducted. A simplified universal electric motor design has been developed that is in the process of being prototyped.

(a)



(b)

Fig. 3 (a) Wire-wound laminated motor core in (b) DC motor configuration

Soft wire-wound iron cores constitute the most important modular component for the rotor and the stator assembly (Fig. 3). The cores are constructed from plastic-laminated layers of silicon electrical steel to minimize eddy currents. This laminated structure lends itself to 3D layered printing–a carousel with alternate FDM and EBF3 printers manufacturing a stack of metal/plastic layers to form the soft iron core. Grooved plastic bobbins may then be printed by FDM as a sheath around the core assembly. An example of another 3D printed multi-material artifact is the dry electrode constructed from a flexible insulating polymer into which conical needles were embedded [25]. However, this is simpler than this motor design. Plastic-coated extruded wires are then wound around the bobbins of the cores. These cores comprise electromagnets required for the central rotor and the peripheral stator elements encasing the core of a universal motor. The rotor is to be immersed in silicone oil.

Displacement sensors for feedback may be implemented as rotary potentiometers (electrical resistors). Magnetic bearings may be employed to exploit magnetic levitation to support the rotor without physical contact. They are highly desirable in flywheel energy storage for minimum friction, especially in a vacuum. This assembly requires a complex assembly process in which a 3D wrist replaces the print head in the FDM printer.

The motor core also provides the basis for constructing an electromagnetic launcher. An electromagnetic launcher (mass driver) may be deployed to disperse each self-replicating unit randomly to other locations on the lunar surface to prevent overcrowding during population growth. The mass driver comprises a magnetically levitated vehicle accelerated by a linear synchronous electric motor. A coil-based electromagnetic mass-driver constitutes the same basic components as an electric motor but in a linear configuration (of larger scale, of course) [26]. The cylindrical armature carries an armature current and resides within a long solenoid (stator) comprising of separate coils. The armature is suspended by magnetic induction from the energized coils to eliminate friction. The coils are energized sequentially like a stepper motor so that the armature accelerates along the solenoid axis.

Solid state electronics cannot be readily manufactured without major infrastructure electrical components of a simple construction have been adopted – resistors (wires), capacitors (plates), inductors (coils) and active devices (vacuum tubes). These are all potentially 3D-printable from a limited repertoire of materials. The first operational amplifiers were in fact constructed from vacuum tube technology. Vacuum tubes are reliable if maintained in the power-on state in a thermally stable environment. Vacuum tubes are less susceptible to radiation than solid state electronics and are still used in microwave technology for communications satellites. Vacuum tubes are also the basis of much microwave technology necessary for solar power satellites. Vacuum tubes are thermionic diodes in which a sintered tungsten resistance wire cathode is heated to 1000-1200^{o}C in an evacuated glass envelope. It may be coated with CaO derived from lunar anorthosite to reduce its work function to operate towards the lower temperature, but this is not essential. The vacuum tube has a relatively simple construction although we have yet to demonstrate its 3D-printability. They have been used in early computing machines-Colossus (1943), the first programmable electronic computer at Bletchley Park comprised of 2400 vacuum tubes. Similarly, the ENIAC computer (1946) used 17,500 vacuum tubes consuming 150 kW and covered an area of 200 m^2. This is not practical. To that end, hardware neural network circuits based on a variation of the Yamashida-Nakaruma analog neuron as the basic computing unit have been adopted – it comprises a weighted input, a summing integrator and a sigmoid output [27].

We have demonstrated a simple two-neuron system in a rover obstacle avoidance application (Fig. 5), but it is readily scalable to more complex problems with only a logarithmic growth of network size with task complexity.

V. In-Situ Resource Utilization

We must now consider the raw material feedstock for our 3D printing system. On Earth, almost 90% of material demand comprises brick and concrete for compressive loading in civil constructions, but this will be much reduced in the case of a lunar infrastructure. Nevertheless, indigenous rock, concrete and/or cement can reduce the demand for structural metal where appropriate in compressive structures. Basalt has long been used in casting in Europe especially high abrasion resistant liners for steel tubing [28]. Glass may constitute 50% of lunar agglutinates in mature soils or up to 100% in pyroclastic soils. Aluminosilicate glasses and silicate ceramics are readily synthesized from lunar regolith and rock through sintering/melting [29]. A thermal lance can sinter lunar regolith into the glass at 1300°C. The lack of water vapor contamination ensures that high purity eliminates glass brittleness. The planned Resource Prospector Mission (RPM) to the Moon will demonstrate the extraction of volatiles from the lunar regolith in 2018. This includes water ice which is known to occur in significant quantities in the lunar polar regions due to impregnation by the solar wind. This constitutes 96% H_2 (~120 ppm), almost 4% He, and trace amounts of H_2O, CO, CO_2, CH_4, N_2, NH_3, H_2S, SO_2 and noble gasses such as Ar. These gasses are preferentially absorbed onto small particles of the ilmenite ($FeTiO_3$) mineral that is abundant in the lunar maria.

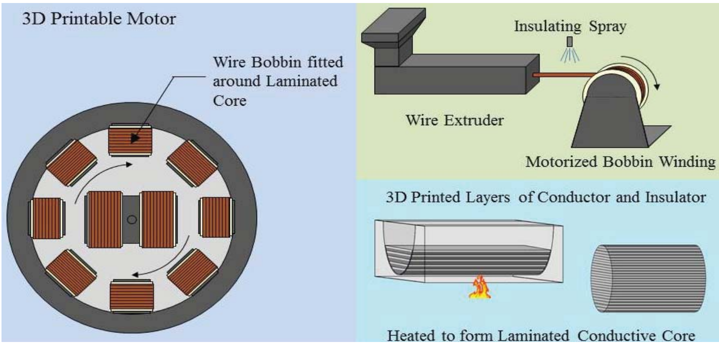


Fig. 4 Universal motor concept and its construction

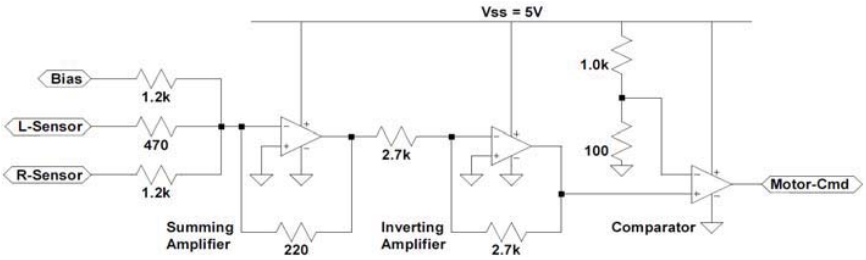


Fig. 5 Circuit representation of a single hardware neuron network designed for obstacle avoidance

In the simplest mining scenario, a mobile rover would scoop surface regolith, subject it to comminution by motor-driven crushing, and magnetic beneficiation. However, RPM will be drilling for its regolith samples and will not employ prior comminution and beneficiation before processing the regolith. The ilmenite grains will be heated to 700°C which will release 90% of the volatiles. If heated to 900°C, sulfur compounds H_2S and SO_2 are also released completing the release of the entire volatile fraction. These can be separated out and condensed through a fractional distillation column: Heat 4.2 K, H_2 at 20 K, N_2 at 77 K, CO at 81 K, CH_4 at 109 K, CO_2 at 194 K and H_2O at 373 K. This would require motorized pumps and stirrers to convey gases and fluids through the unit chemical processes. Plastics are useful materials as flexible electrical insulation, but C is depleted on the Moon. However, silicones $(R_2SiO)_n$ have O-Si-O backbones, reducing the C inventory requirement - they are versatile, highly heat resistant and are radiation resistant. Syngas may be converted to silicone plastic with SiO_2 from silicate lunar minerals, but this requires Cl import from Earth as a recyclable reagent [30]. Plastics in general, and silicone plastics, in particular, offer great versatility - arrays of elastomer-based whiskers offer the possibility of tactile sensing [31]. RPM will demonstrate hydrogen reduction of ilmenite to extract oxygen at 700-900°C within a reaction chamber for 1-3 hours:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$

$$2H_2O \rightarrow 2H_2 + O_2$$

H is recycled. Ilmenite (Apollo 12 sample) is composed of 52-54% TiO_2, 45% FeO, 0.3-04% Al_2O_3, 0.2-0.4% Cr_2O_3, 0.1-0.4% MgO and 0.3-0.4% MnO. Although RPM will not recover Fe or rutile (TiO_2), Fe is a highly versatile material for an iron-based industrial infrastructure -wrought iron is near-pure Fe that is tough and malleable for tensile structures; cast iron with 2-4% C and 1-2% Si is a more brittle structural material for compressive structures; ferrotungsten tool steel with <2% C with 9-18% tungsten is hard, resistant to abrasion, and resistant to dulling of cutting edges; fernico is family of iron alloys that include Ni and Co for high electrical conductivity and a thermal coefficient of expansion that matches that of glass - an example is kovar alloy with 53% Fe, 29% Ni, 17% Co, 0.2% Si and <0.01% C giving it high electrical and thermal conductivity for electrically conductive strips through glass seals such as those found in vacuum tubes; invar with 64% Ni and 36% Fe also has low thermal expansion; ferrosilicon (silicon electrical steel) with up to 3% Si and 97% Fe is highly electrically resistive and used in iron cores of motors and transformers. Tungsten is malleable so it can be forged drawn or extruded. Rather than introducing the complexity of extracting Ti from titania (TiO_2) residue, it may be extruded into fibers for thermal insulation or fibre-reinforced composites. SiO_2 can be extracted from anorthite (fluxed with oxides to reduce anorthite viscosity) through carbothermal reduction. Other potential sources of ceramic include mare basalts, olivine, and pyroxene. Quartz does not occur naturally on the Moon, but it may be grown from native silica glass in lunar regolith. Silica is melted at 2000^{o}C followed by seeding in $Na_2(SiO_2)_nO$ (formed from Na_2CO_3 reaction with SiO_2 at <900^{o}C) at 350^{o}C and 150 bars. Sodium silicate is often used in drilling muds to stabilize boreholes. The Na is a required import from Earth but is recycled as a reagent. Quartz is piezoelectric and serves two functions – the basis for force sensing and a radio-frequency oscillator in a simple Pierce circuit.

Although mining of surface regolith can be accomplished with a simple scoop mounted onto a rover, infrastructure development will be more complex. In the same way that biological processes are encapsulated within the controlled environment of the biological cell, any artificial self-replication process should occur within a controlled workspace to enhance robustness in the face of environmental perturbations [32]. This may be as simple as a paved environment with solid jigs for enabling assembly of components. A paved surface would minimize dust generation during surface operations. The 100 tons Freitas lunar seed factory concept began with fusing the lunar surface regolith for a 50m radius. The workspace must also be encapsulated in a well-defined enclosure to control the internal environment. Site preparation at a minimum shall require some means of leveling, trenching and roadway or railway construction. This implies extensive surface operations on the Moon involving haulage, transport, cargo handling and construction activities. Cargo handling includes cranes whereas haulage methods include conveyors, cables, rail trams, pipelines and electromagnetic transport. An autonomous drag-line excavator has been demonstrated with automated digging and dumping whilst accounting for terrain and regolith variability using laser scanning of its environment [33]. Dragline involves dragging of the bucket through the soil, hoisting the bucket and slewing the bucket for dumping. For a regolith excavator, the soil failure force during digging may be computed from the Mohr-Coulomb relation in predicting required digging forces [34]. Mohr-Coulomb models have been implemented in neural network form [35].

Certain materials such as Ni, Co and W are scarce on the Moon and require access to the Ni-Fe asteroidal material. Distortions in the lunar gravity field (mascons) indicate buried metal asteroid material such as at the rim of the South Pole-Aitken Basin. Nickel-iron asteroids constitute a Ni source often with Co contaminant - both Co and Ni may be extracted magnetically. They are often enriched in tungsten microparticle inclusions - tungsten's very high density of 19.3 times that of water presents a simple means for its separation from other elements. There is, in addition, significant amounts of siderophile elements such as Pt (useful as a potential catalyst).

The processing of local lunar resources will require significant amounts of thermal energy. A lunar solar furnace comprises a tungsten crucible onto which parabolic mirrors or Fresnel lenses concentrate solar power generating 1600^{o}C or 2700^{o}C respectively. For mirrors, metals, in general, have high reflectivity [36]. Steel can be polished to create ~75% reflectivity whereas nickel offers reflectivity ~80-85%. The solar furnace is capable of sintering (regolith), smelting (metal-containing minerals) and/or vacuum pyrolysis. High purity SiO_2 may be heated into the glass at temperatures of 1700^{o}C. Precision glass moulding offers the prospect for complex lens geometries such as Fresnel lenses or other optical components without grinding or polishing. Precision glass moulding begins with a near-spherical glass blank inserted into a 3D printed precision mould of steel and heated to the working temperature between the transition temperature and glass softening temperature. The mould is closed and compressed under a controlled force. The glass is slowly cooled and removed from the mould. Convex shapes such as Fresnel lenses are readily moulded with surface roughness <3 μm. Although most energy requirements will be for thermal energy, electrical energy will also be required. To convert thermal energy into electrical energy, thermionic emission has been used in nuclear reactors offering efficiencies of 5-20%. Thermionic converters are vacuum tubes, and even primitive thermionic emission can be expected to yield around 10% efficiencies, significantly higher than that expected from amorphous silicon-based photovoltaic cells of 1-5%. Energy storage over the lunar night may be implemented through motorized flywheels with magnetic bearings.

The only imported materials required are recyclable reagents Na and Cl - NaCl may be dissolved in aqueous solution, but electrolysis of aqueous NaCl yields only chlorine: $2NaCl + 2H_2O \rightarrow 2NaOH + H_2 + Cl_2$. To recover Na as well, electrolysis of molten NaCl at 800^{o}C with a Fe cathode and C anode is required: $2NaCl \rightarrow 2Na + Cl_2$. This requires a potential difference of only 4.07 V. The apparent disadvantage of Earth imports can be converted into an advantage – it effectively implements a "salt contingency" as a safeguard against uncontrolled replication.

VI. Lunar-Constructed Geoengineering Modules

Once the self-replicating factories have reached their final desired population, they may be reprogrammed to construct solar shield modules. The purpose here is to demonstrate that using the same materials and processes outlined earlier; we can manufacture a spacecraft that may be employed to form part of a solar shield.

The solar shield modules may be launched into lunar orbit by electromagnetic launchers without minimizing the

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consumption of fuel. Spacecraft-containing buckets are accelerated to launch speeds. From the Moon, an electromagnetic launcher must launch into L1 transfer orbit at 3 km/s – this is easily within reach of modest electromagnetic launchers compared with 12 km/s required from Earth. On the Moon, a 15km track can provide 30g continuous acceleration using 2T superconducting magnets. Alignment and precision are the critical requirements to ensure accurate rendezvous targeting. Large amounts of electrical energy must be stored for release during launches – flywheels are currently used at the JET Torus for high power densities and the ability to supply high power over short release times.

For in-space propulsion, solar sails are the system of choice as they involve no fuel. Thin films of steel or Ni may be deposited either onto silicone polymer sheets or accumulated into metal foils. Electron beam physical vapor deposition is a form of physical vapor deposition of thin films through energetic electron bombardment (~20 kV) of a target material by an electron gun into a vapor. It occurs at lower temperature than chemical vapor deposition and without corrosive chemicals. It has a high deposition rate but cannot coat inner geometric surfaces – this is not a requirement for a solar sail. Sputter deposition is a form of physical vapor deposition for depositing thin films. Sputtering sources involve magnetrons to generate high electric and magnetic fields to confine a plasma. An inert gas such as Ar (that exists in lunar regolith in small quantities) yields more plasma for a higher deposition rate. Sputtered atoms are neutral and unaffected by the magnetic field. For a pure iron film sail with a density of $\rho=7.87 \times 10^6$ g/m^3, the minimum thickness for a solar sail is 12 μm. This is a best case scenario – more useful accelerations require thinner sails. This requires further investigation. However, compressed propellant H_2 and oxidizer O_2 may be manufactured from lunar volatiles and subjected to passive cooling in relatively high quantities. Tankage and thrusters of iron and steel respectively may be lined with tungsten. Hence, conventional hydrogen/oxygen fuel is readily available.

All other elements of the spacecraft – structure, mechanisms, attitude control, power generation/storage, thermal control, command and data handling, and communications – are all derivable from the self-replication capability. Wrought iron may be used for the primary and secondary structures – wrought iron is ideal for load-bearing. 3D printing offers greater flexibility in structural design such as iso grid and monolithic truss designs. Motorized mechanisms for deployable may employ electric motors as described earlier. Attitude control may employ reaction wheels, momentum wheels or control moment gyroscopes driven by the electric motors as described. Station-keeping may be implemented through a number of techniques such as potential fields, neural fields, flocking algorithms, etc. [37]. Thermal control may be based on passive systems such are thermally conductive straps of fernico, thermal insulation with glass and titania fibers, radiators of polished steel, or active methods that rely on resistance wire heaters and electric motors such as louvers, etc. Data handling may be implemented through a combination of vacuum tube based analog circuits, analogue-based logic circuits, and neural network controllers. The communications subsystem is similar in concept to the data handling subsystem in that electronics plays a central role. Quartz is ideal as a radio-frequency oscillator – the Pierce oscillator may be constructed with a minimum number of components – one inverter, two resistors, two capacitors and one quartz crystal. The mixer is a transistor/diode circuit constructible from vacuum tubes, the filter is an RCL circuit, the amplifier is a traveling wave tube amplifier (TWTA), and the demodulator is a diode. Traveling wave tube amplifiers, klystrons and magnetrons are based on vacuum tubes. Hence, a simple communications system may be implemented using vacuum tube technology.

Power generation in space may derive from the lunar method – solar concentrators concentrate light to high heat onto thermionic converters which output electrical energy with a conversion efficiency of 10%. This obviates the need for photovoltaic panels. For short duration eclipsing, rechargeable NiFe batteries using a KOH electrolyte (extracted from KREEP basalts) are a robust form of short-term energy storage though with the low specific energy of 25 Wh/kg – they were used to power the German V2 rockets. Long duration power storage may use flywheels, possibly combining power storage with attitude control.

The payload of the solar shield is the refracting lens of its main structure – this has been described earlier. Hence, all the major subsystems and functions of a spacecraft – and a solar shield module specifically - can be derived from self-replication capacity. There is thus no reason why a self-replicating machine (or more properly, a universal constructor) on the Moon cannot construct multitudes of spacecraft deployed as a solar shield constellation. The multiplicity of such machines lends itself to the rapid and parallel production of millions of such modules. Indeed, self-replication capability eliminates the launch cost barrier to space-based technological solutions to climate change.

VII. Conclusions

The approach presented here addresses the key criticisms leveled against geoengineering: (i) lack of reversibility; (ii) discouragement to long-term clean energy solutions. The cost of doing nothing will soon exceed the cost of implementing geoengineering - with self-replication technology the costs can be reined in enormously. There is an argument that geoengineering should proceed in conjunction with clean energy capacity building. This is precisely the advantage of the solar shield with solar power satellite combination. The prospect of failure of the space-based approach is less likely as it is grown through self-replication and is as a consequence self-repairable. An ethical argument is that implementation of geoengineering attacks the symptoms rather than the cause- this is true for the most part but does not apply to the space-based approach as it lays the foundations for constructing solar power satellites from lunar resources. Geoengineering may be regarded as morally permissible if the following conditions hold [38]: (i) project is technically feasible (the topic of this paper); (ii) its consequences can be predicted (its predictability is better than other solutions); (iii) it generates preferable socio-economic activity to status quo (this is true in that geoengineering is designed to prevent the worst effects of global warming); (iv) geoengineering does not violate any ethical principles (geoengineering is designed to reduce loss of life and livelihoods as a consequence of global warming). We, therefore, submit that self-replication technology offers the key to developing low-cost, short-term solutions (space-based geoengineering) and long-term solutions (solar power satellites) to our current and future global climate problems.

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